

## Control Approaches for a Dissipative Passive Trajectory Enhancing Robot

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### Abstract

A mechanically passive device is described which, when controlled by an appropriate algorithm, restricts the user to move the tip of the device along a specified but arbitrary path. One advantage of such a device is safety from malfunctions of the controlling actuators. A novel approach for controlling such a device is presented, along with some results of the control algorithms that were implemented on the testbed device.

### 1. Introduction

Devices which assist the user with precise movements of a hand or arm, used to be indispensable to almost every mechanical engineer or architect who drafted. The devices guide a pencil tip and are known as rulers, templates, and French curves. These devices are limited to a single shape and to two dimensions. This research focuses on a device which strives to achieve a programmable "ruler".

### 2. Other's Work

The most notable work, to this author's knowledge, is the work of Colgate, Peshkin, and others, in their papers on non-holonomic Programmable Constraint Machines.[2,6] These devices are able to achieve the goal of a modifiable "ruler" extremely well, but the approach taken is very different than the approach explored in this research. One application of

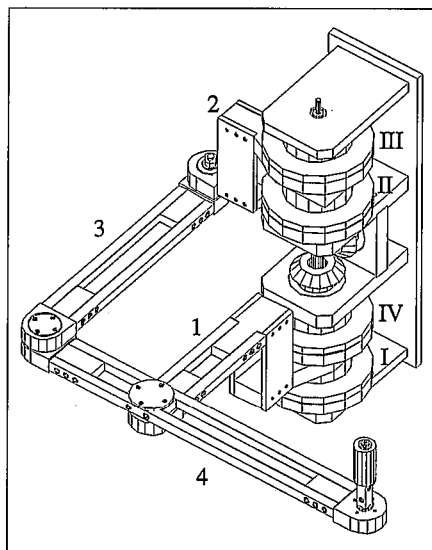


Figure 1: Schematic of PTER

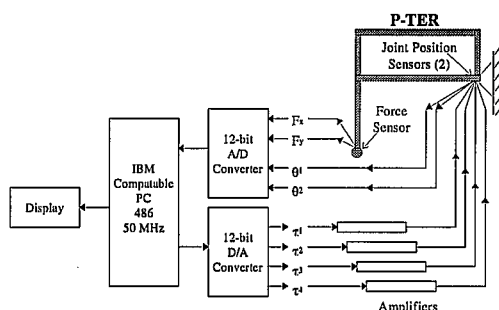


Figure 2: Components of PTER

these devices is in the medical field and a paper by Troccaz and Lavallee describes a device, a PADYC, which has a somewhat different, but similar goal as these other devices.[7]

### 3. Testbed Description

The device used in this research is known as a Passive Trajectory Enhancing Robot, or PTER.[1] PTER, depicted in Figure 1 is two degree of freedom device which, when unconstrained, can be moved freely in a horizontal plane. The angular positions of the links 1 and 2 are measured using potentiometers. The force applied at the tip of the device is also measured by a strain gauge force sensor. A schematic of the components which make up PTER is shown in Figure 2. The two degrees of freedom can be affected by any of the four clutches which are located on the main axis of the device and labeled I-IV in Figure 1. The four clutches are attached to the links, labeled in Figure 1, and base of the device as listed in Table 1.

Table 1: Clutch list

	attached between ...	
clutch I	base	link 1
clutch II	base	link 2
clutch III	link 1	link 2
clutch IV	link 1	-link 2

Clutches I and II can be excited so that they tend to slow down and stop any motion of links 1 and 2 respectively. Clutch III and IV, when excited, couple the

motion of links 1 and 2. Clutch III tends to make the velocities of link 1 and 2 equal, whereas clutch IV tends to make the velocities of link 1 and 2 equal in magnitude but in opposite directions. Clutch III, because of its capability is called the direct coupling clutch and is depicted in Figure 3.

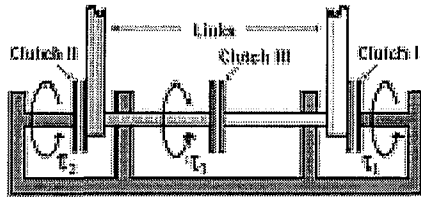


Figure 3: Direct coupling mechanism

Clutch IV, depicted in Figure 4, is known as the inverting coupling clutch since it tends to make links 1 and 2 move in opposite directions.

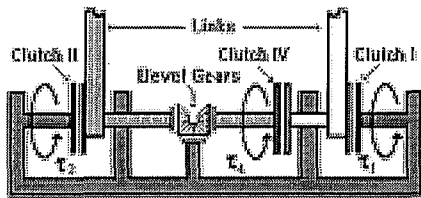


Figure 4: Inverting coupling mechanism

#### 4. Friction Model

The friction model assumed is the basic Coulomb friction law. Examining a clutch which uses that model leads to some insight on the limitations that are imposed by using clutches to control the device.

For purposes of understanding, let us imagine a very simple single degree of freedom system, a bar attached to clutch which has its other half attached to ground. When the link is moving, the clutch can only provide torques on the link in a direction which is in the opposite direction to the link's rotational velocity. When the link is motionless and the clutch is active, the magnitude and direction of the torque that the clutch can apply to the link does not depend upon the velocity of the link, but instead is a function of the externally applied force on the link's tip. For a given excitation level to the clutch, there will be a maximum torque that the clutch will be able to resist until it begins to slip, that is the nature of the dry friction model that is being used. In the applied force range below the slipping force, the magnitude of torque that the clutch can apply on the link is exactly the same as the applied force perpendicular to the link times the distance from the joint to the point of application of the force. The direction of the

clutch torque on the link opposes that of the torque on the link due to the applied force. Thus the torques that the clutch is able to provide to the link are limited in magnitude and direction depending upon the current state of the device. This one dimensional device is very representative of each of the four clutches that are present on PTER.

#### 5. Clutch Model

The clutches that are being used have previously been considered to act instantaneously, which is definitely not the case. A first order dynamic model was assumed for the operation of the clutches using the applied excitation voltage as the input, and the clutch torque applied to the link as the output. After running a crude experiment using a step input to a single clutch and assuming constant angular velocity during the test, a time constant of 0.25 to 2.5 seconds was obtained.

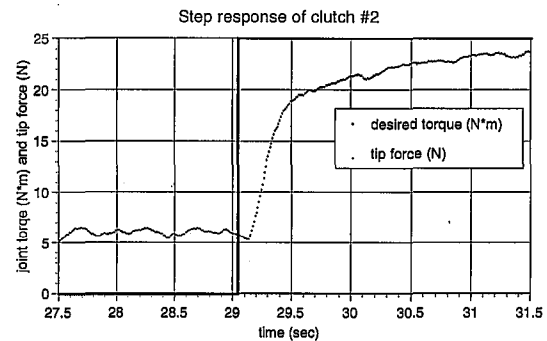
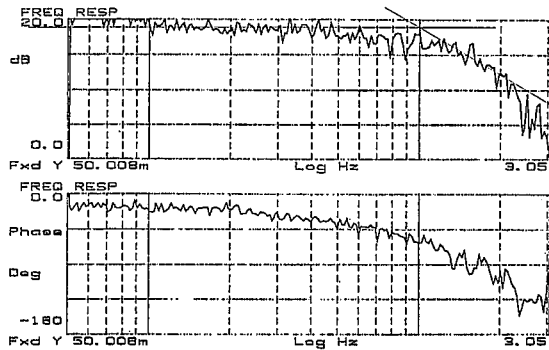


Figure 5: Step response of clutch #2

Upon further analysis of the links' accelerations during the test, it was found that a second different test should be conducted to obtain a second value of the time constant. Using a digital signal analyzer, a frequency response of the system with one clutch locked and the other clutch moving at a relatively constant rate was obtained. The frequency response obtained, shown in Figure 6, was for a force measurement as output and clutch voltage excitation as input.



6: Frequency response of clutch #2

This experiment gives a cutoff frequency of about 0.6 Hz, 3.77 rads/sec to 1.0 Hz, 6.28 rads/sec. These cutoff frequencies correspond to time constants 0.27 and 0.16 seconds respectively. Although these two tests combined give a range of time constant values, they do demonstrate that the time constants are fairly sizable and must be compensated for in the control algorithms.

## 6. Previous Control Algorithms

Hurley Davis developed a control algorithm on PTER which uses an active algorithm to calculate the desired joint torques on link 1 and 2.[3,4] However, not every desired control torque can be applied to PTER since it is a passive device. Davis devised a Torque Translation algorithm, which tries to apply those desired joint torques if possible. If the desired control torques can not be applied, the torque applied will be a compromise between what is desired and what is possible. This control algorithm resulted in fairly accurate path following but the clutches were pulsed on and off in rapid succession resulting in a very jerky motion. This has to do with the fact that the 1st order approximate dynamics of the clutches was not taken into account.

## 7. A Different Control Algorithm

This control algorithm does not use an "active" controller to calculate desired torques and then use the constraints of passivity to decide if a certain control torque can or can not be applied with the clutches. Instead, this algorithm examines what can be done with the clutches from the outset and derives the control torques from that, taking the passivity constraints into account in the beginning.

Before discussing the intricacies of the control algorithm, some background must be explained. The first thing that needs explanation is the tip force diagrams. A clutch can be used to provide a torque on a link at the main

joint axis. This torque can be transformed to the tip where it appears as a force. One can visualize the transformation by picturing the following situation, depicted in Figure 7.

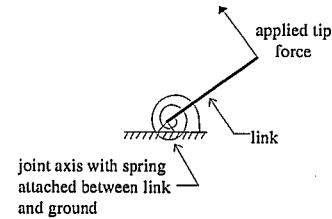


Figure 7: Joint torque to tip force transformation example

Imagine a single link attached to an immobile base by a pin joint with a torsional spring connected between the base and link. Imagine rotating the link by 360 degrees (CCW) so that the link is in the original orientation and the spring is now loaded. The spring is applying a torque on the link at the joint, and your hand is applying a force on the link at the tip which is keeping the link motionless. The joint-torque to tip force transformation would transform the joint torque applied by the spring to a tip force which would have to be *opposed* by your hand in order to keep the link motionless. It is these forces that will be discussed later in the explanation of the control algorithm and its performance.

The next thing that must be discussed is tip velocity diagrams. If a single clutch is locked up on PTER, then the previously two degree of freedom system, becomes a single degree of freedom system with a defined tip path. The direction that the tip will go along this path is determined by the velocity of the tip before the clutch is locked. Thus, at any given state of motion of the device, there is a specific instantaneous velocity direction associated with the locking up of each of the four clutches. To demonstrate the idea, imagine a two degree of freedom Cartesian device with prismatic joints, depicted in Figure 8. There are two clutches, one for each degree of freedom.

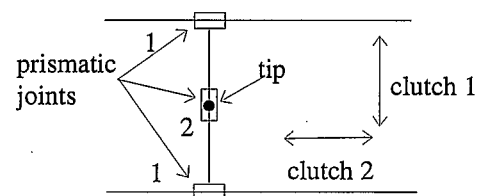
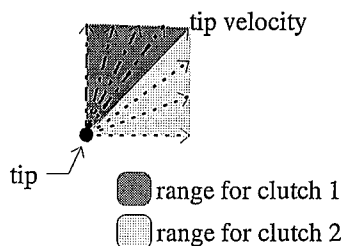


Figure 8: Tip velocity diagrams example

If clutch number two is locked, then the tip can not move along the bar, but the bar can still translate in the

horizontal direction. Thus the instantaneous velocity direction for the tip will be horizontal, pointing either left of right depending upon the velocity of the tip before clutch two was locked. A similar scenario follows if clutch one is locked, resulting in an instantaneous velocity in the vertical direction.

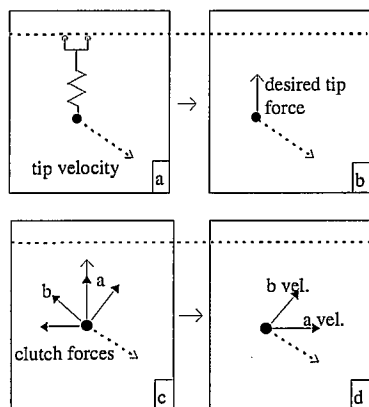


**Figure 9:** Modified tip velocities possible with each clutch for the device in Figure 8

Figure 9 shows the importance of the tip velocity diagrams. Given a tip velocity in a direction 45 degrees to the horizontal, clutch one is able to redirect the tip velocity so that it points more towards the vertical. This redirection is possible by applying the clutch so that it slips and does not lock up. By increasing the amount of force that clutch one applied to the joint, it is possible to redirect that tip velocity so that it points closer and closer to the vertical direction. Clutch two can only redirect the tip velocity so that it points more towards the horizontal. Although it is a fairly simple concept, it becomes very useful when deciding which clutch to use when trying to control PTER.

## 8. Previous control algorithm re-visited

A simplified example of the previous control algorithm and its limitations can be seen in Figure 10.

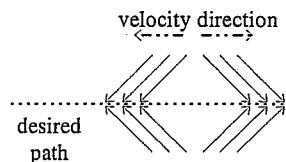


**Figure 10:** Examination of previous controller

Figure 10a shows the simplified active controller, acting like a spring force to return the tip to the desired path, which is used to calculate the desired control torques. Figure 10b shows the desired tip force due to the spring along with the instantaneous measured tip velocity. Figure 10c shows the four tip forces (translated from joint torques) that the four clutches can provide. Of special note is clutch force "a" which is in exactly the same direction as the desired tip force. Davis' algorithm would choose clutch "a" to provide the desired tip force. However, if we examine the velocity diagrams for these four clutches we see something interesting. Figure 10d shows the tip velocity diagrams for clutches "a" and "b" from Figure 10c. By using clutch "a" to provide the desired tip force, the tip velocity can only be redirected to at most a horizontal line, in this case by locking clutch "a". However in order to redirect the tip velocity so that it points back toward the path, clutch "b" should be used, which is not easily seen in Figure 10c. The new controllers use these clutch velocity directions to pick a clutch to use in redirecting the tip velocity.

## 9. Results of the new controllers

The first controller to be discussed attempts to restrict the tip motion to be a straight line in the workspace by on/off control with at most one clutch active at a time. The clutch chosen is the one with the locked clutch velocity line which is closest to the desired tip velocity line as seen in Figure 11.



**Figure 11:** Desired return velocity directions

This method of prescribing desired velocity lines based on position is similar to the approach outlined by Li and Horowitz.[5] However, the algorithm used in this research is much simpler than the one described by Li and Horowitz.

The results from an experiment with a user pushing on the device while this control algorithm was being run is shown in Figure 12.

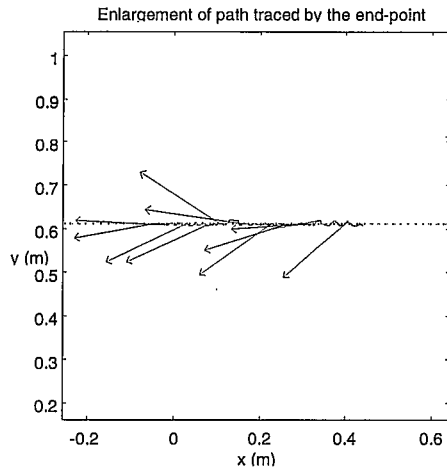


Figure 12: Results of on/off controller

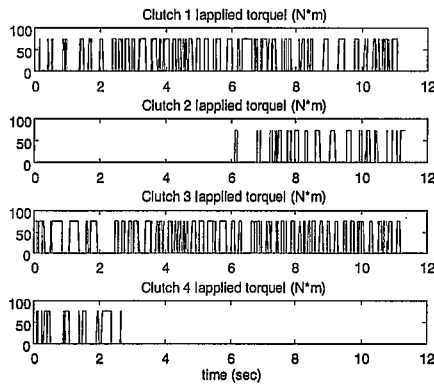


Figure 13: Control signals from on/off algorithm to clutches

Some things to be noted about this algorithm are that Figure 12 shows fairly accurate path following with the user pushing away from the desired path on both sides of that path. Figure 13 shows that the clutches are being pulsed on and off and that at any given time, only a single clutch is active. The tip accelerations reach a maximum magnitude of around  $1.25 \text{ m/s}^2$  with an average tip acceleration of  $0.4 \text{ m/s}^2$ , which is indicative of rough motion. One problem with this controller is that although it is accurate, it does result in very “jerky” motion. This jerkiness is due to the instantaneous changes in clutch excitations given by the control algorithm. Two things which must be done to eliminate the discontinuities in clutch excitations are to change the on/off nature of the brakes to something continuous. A blend must also be created when switching between two clutches when it becomes more desirable to use one clutch over another.

This algorithm also will not completely stop the user if he or she is pushing directly away from the desired path. This is because the algorithm uses at most one clutch at a time, never two, so the device always has one degree of freedom. Thus the tip can be pushed off of the path if there is no way that the clutches can bring it back onto the path.

The second controller that will be examined solves many of the problems of the on/off controller, but at a cost of less accurate path following. The on/off nature of the clutches is replaced with a excitation level which is proportional to the distance that the tip is from the path. The switching of the clutch problem was solved by keeping the switching of the brakes a minimum and by using a blend for instances where a switch is needed. This blend is dependent upon the locked clutch velocity directions, and the current tip velocity direction, and is depicted in Figure 14.

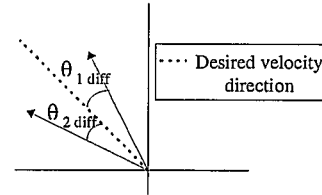
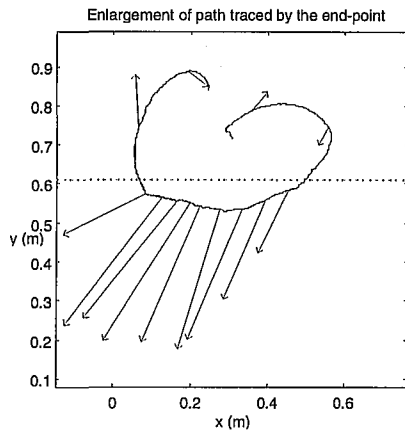


Figure 14: Clutch choice blending algorithm

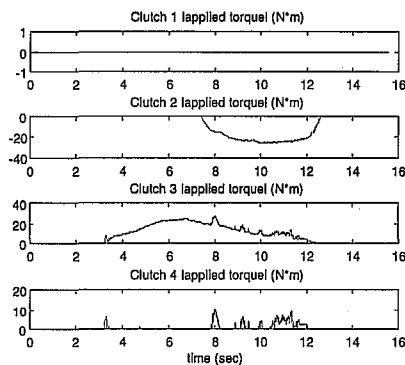
$$\text{weight for clutch \#2} = \frac{(|\theta_{1diff}| - |\theta_{2diff}|) + \text{window}}{2 * \text{window}} \quad (1)$$

**n.b.:** *window* is a user defined variable which controls the range over which the blend will take place. Equation 1 is only valid for  $\text{weights} > 0$  and  $\text{weights} < 1$

Something else that is accounted for in this algorithm is the ability to stop the tip when the user is pushing in a direction that cannot bring the tip back towards the path. Clutches III and IV are used to stop the device if such a situation occurs. Since the direction that the clutches can apply torques become dependent upon the tip force direction at zero velocity and the tip velocity direction at non-zero velocities, a blend was needed at low velocities between the applied tip force and tip velocity directions. The results of the algorithm applied to a different scenario than before, a virtual wall situation where free space is located above the desired path, is shown in Figure 15.



**Figure 15:** Results of improved controller



**Figure 16:** Control signals from improved algorithm

As can be seen by Figure 15 the results of this algorithm show a smoother restricted path than the on/off algorithm's results. The maximum tip acceleration is around  $0.3 \text{ m/s}^2$  with an average tip acceleration of around  $0.15 \text{ m/s}^2$ . However, this smoothness was achieved at a sacrifice of tip path accuracy.

## 10. Acknowledgments

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